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Andersen, Torben Ole; Pedersen, Henrik Clemmensen; Hansen, Michael Rygaard

Publication date:
2007

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Andersen, T. O., Pedersen, H. C., & Hansen, M. R. (2007). *Mechatronic System Design Based On An Optimisation Approach*. Paper presented at International Workshop - Mechatronics Day 2007, København, Denmark.

MECHATRONIC SYSTEM DESIGN BASED ON AN OPTIMISATION APPROACH

Torben O. Andersen
Aalborg University
Institute of Energy Technology
DK-9210 Aalborg East, Denmark
Phone +45 9635 9269, Fax +45 9815 1411
E-mail: toa@iet.aau.dk

Henrik C. Pedersen
Aalborg University
Institute of Energy Technology
DK-9210 Aalborg East, Denmark
Phone +45 9635 9275, Fax +45 9815 1411
E-mail: hcp@iet.aau.dk

Michael R. Hansen
Aalborg University
Institute of Mechanical Engineering
DK-9210 Aalborg East, Denmark
Phone +45 9635 9321, Fax +45 9815 1411
E-mail: mrh@ime.aau.dk

ABSTRACT

The envisaged objective of this paper project is to extend the current state of the art regarding the design of complex mechatronic systems utilizing an optimisation approach.
We propose to investigate a novel framework for mechatronic system design. The novelty and originality being the use of optimisation techniques. The methods used to optimise/design within the classical disciplines will be identified and extended to mechatronic system design.

KEYWORDS: Mechatronic System Design, Optimisation, Modelling, Simulation, Control.

1 INTRODUCTION

Throughout the last half century, the requirements for new products and systems have radically changed, driven by the need of manufacturing more advanced, better and efficient products, in order to stay competitive. Today it is no longer enough to design a product which fulfils its intended task satisfactorily, it needs to be more efficient, versatile, unique and cost-effective than other similar products in order to be competitive.

Mechatronic systems and products here pose new opportunities, as the combination of the different technologies may not only open for designing simpler systems, where e.g. a complex mechanical system is replaced by an actuator solutions, but may also bring with it new features and functions, that could not earlier be realised with only one technology. The latter exemplified through e.g. fault monitoring systems and active damping. Designing mechatronic systems however pose new problems due to the interaction of technologies. There are many designs where electronics and control are combined with mechanical components, but with very little synergy and poor integration they just become a marginally useful, error-prone, expensive conglomeration. Synergism and integration in the design process is what set apart a *Mechatronic System* from a traditional, multidisciplinary system, but this also adds new complexity to the design process. The design process is in this way not only further complicated by the addition and mixing of technologies, but also the by the circumstances that changing one or more design parameters may highly influence a complete design, where the effects may not be foreseen up front, but is left to be analysed afterwards, as the correlations are typically highly non-linear.

The typical design approach has been to divide the design problem into sub problems for each technology area (mechanics, electronics and control) and describe the interface between the technologies, whereas the lack of well-established, systematic engineering methods to form the basic set-off in analysis and design of complete mechatronic systems has been obvious. This lack of methods is among other complicated by the following reasons:

- Insight (theoretical) into each of the technical disciplines are required to fully understand the possibilities and limitations in the different technologies and the advances and limitations that may arise when interacting.

- When considering actuated mechatronic systems, i.e. systems that include moving parts, many problems are of extremely dynamic nature and can only be described by differential equations.

- Many components have inherently non-linear characteristics, making the describing differential equations non-linear and thus limits the applicability of linear control theory.

- Mechanical systems and some actuation system types (hydraulic and pneumatic) are in fact distributed parameter systems. It takes some skill to make sound engineering judgements on when and how lumped parameter approaches can be made and/or when rigidity (i.e. structural flexibility) significantly influence the dynamic behaviour.

- Finally the development of valuable engineering theories very often must be based on experimental verification of hypothesis.

The problem or engineering effort in mechatronics is therefore both of educational and technical nature.

It seems from the above statements, that strong efforts in the elevation of the engineering methods ought to be emphasised as one mean to ensure that the full potential in mechatronic systems are utilised, hereby ensuring the companies a continuous ability to compete. Optimisation methods combined with modelling and simulation of systems here form the promising basis for a design approach that may ensure optimal systems, when also using the well-established methods from control engineering, which forms very powerful techniques both in the analysis and in synthesis of multi-technology (mechatronic) systems. Before control-engineering techniques may be applied it is, however, required that components and problems may be described (modelled) in terms compatible to the "language" used in control engineering. This means, that the behaviour of components and systems must be expressed as static and dynamic characteristics, transfer functions etc. Thus the disciplines of describing the general system dynamics, doing simulation and laboratory measurement are needed for the physical-mathematical dynamic modelling, efficient handling and solution of the complex describing equations, and experimental evaluation of models. Finally, all these activities loose most of their sense, if they are not based on a broad knowledge and experience of the intended application, i.e. the environment or surroundings in which the mechatronic system should work or be a part of.

1.1 Modelling and Simulation as Prerequisites for the Design Process

The control engineering approach has here been legitimated through the above paragraph, and maybe the most characteristics feature is the use of dynamic models and simulation, which can be worked out to more or less sophistication depending on the level of analysis relevant to the actual problem. Hence, it is important to concentrate engineering research and development efforts in this fields, to establish some of the necessary tools.

Generally, savings in work or cost are the essential reasons why experiments are carried out with models instead of real systems. However, some situations occur in which no alternative to model-experiments exist. This is particularly the case when dealing with systems in which possible instability may initiate irreversibly accelerating processes with hazardous and incalculable consequences. Other good reasons for using simulation in both analysis and synthesis are well known and can be stated as:

- The physical system is not available. Often, simulations are used to determine whether a projected system should ever be built.
- The cost of experimentation is too high. Often, simulations are used where real experiments are too expensive. The necessary measurement tools may not be available or are to expensive. The system might be used all the time and taking it "off-line" would involve unacceptable cost.
- The time constants of the system are not compatible with those of the experimenter. Often simulations are performed because the real experiment executes so quickly that it can hardly be observed.
- Control variables (disturbances), state variables, and/or system parameters may be inaccessible. Often, simulations are performed because they allow us to access all inputs ad all state variables, whereas in the real system, some inputs may not be accessible to manipulation and some state variables may nor be accessible to measurement. Simulation allows us to manipulate the model outside the feasible range of the physical system.
- Suppression of disturbances. Often, simulations are performed because they allow us to suppress disturbances that are unavoidable in the real system. This allows us to isolate particular effects, and may lead to better insight into the system behaviour.
- The number of parameters to adjust in the experiment are too large, giving a huge number of possibilities and at best, result in a sub-optimal solution.

The most important strengths of simulation, but also its most serious drawbacks, are the generality and ease of its applicability. It does not require much of a genius to be able to utilize a simulation program. However, in order to use simulation intelligently, (having the handle to make the real world behave the way we want it to), we must understand what we are doing. Danger lies in forgetting, that the simulation model is not the real world, but that it represent the world under a very limited set of experimental conditions.

Simulations are rarely enlightening. In fact, running simulations is very similar to performing experiments in the lab. We usually need many experiments, before we can draw legitimate conclusions. Correspondingly, we need many simulations before we understand how our model behaves. While analytical techniques (where they are applicable) often provide an understanding of how a model behaves under arbitrary experimental conditions, one simulation run only tells us how the model behaves under the one set of experimental conditions applied during the simulation run. Therefore, while analytical techniques are generally more restricted (they have a much smaller domain of applicability), they are more powerful where they apply. So, whenever we have a valid alternative to simulation, we should, by all means, make use of it, i.e. whenever we have a system with an approximate linear behaviour.

However, as the level of analysis is elevated, as it for instance may happen in connection to development of new components or new systems, a barrier will appear at a certain level. The complexity which underlines the development of mechatronic systems should be recognised.

Very few people are capable of making models of real mechatronic systems, and even though simulation programs are appearing on the market that claims they can simulate pretty much anything, there are still the number of parameters to adjust and the programs can not design the system for you.

In the authors view, confidence in the modelling is central to the potential success of any type of simulation based automated design procedures. This requires that any system should be build up by sub-structures/models that have well known characteristics, are well understood and preferably are experimentally verified in some way at an earlier stage. In the following this approach will be referred to as: **PDP** = **P**redictable **D**esign **P**erformance. Hence, system design should be based on well known sub-systems if the desired reduction in dependency on prototypes is to be obtained. The main drawback of this is, that according to a performance index only, PDP will almost certainly never produce the optimal design as compared to what could be theoretically be obtained using an ideal approach involving development of prototypes, experimental work and application of computational tools, i.e. FEM and CFD. This approach is referred to as: **ODP** = **O**ptimal **D**esign **P**erformance. However, by including development time or "time to marked" the PDP will be capable of producing the best performance in a certain time, thereby acting as a kind of "best practice".

1.2 Automated Design Procedures - Optimisation

Turning our attention to automated design procedures, they are classically referred to as optimisation. In textbooks for engineering students, design procedures for e.g. mechanical mechanisms, are classically divided into structural and dimensional synthesis although experience seems to indicate that this division in most cases is somewhat artificial. The reason for this is that an evaluation of a certain structure/topology cannot be carried out without the dimensional synthesis/sizing unless the structure is clearly unsuitable in the given case. Structural and dimensional synthesis should be approached as an integrated design task that involves the determination of both topology and dimensions. Basically, this may be done in two distinctly[1] different ways as seen from an algorithmic point of view:

- Serial
- Concurrent

In serial synthesis the approach may roughly be described as follows: Topologies are generated before hand based on experience or, alternatively, some kind of automated topology gen-

[1]Combination of the two methods in multi-level optimisation is possible, see e.g. [21].

eration. Next, the actual sizing is carried out, typically by means of some sort of minimisation technique. Finally, the optimised/sized topologies are compared and the best one is chosen.

In concurrent synthesis the topology and the dimensions are varied simultaneously introducing a number of challenges with respect to modelling and sensitivity analysis. These challenges need to be met in such a way that objects, e.g. an actuator or a sub-linkage, may either appear or disappear as well as having their design parameters varied continuously.

On top of that, both serial and concurrent approaches needs to handle the numerical problems associated with the mixing of discrete and continuous parameters, since a typical system is composed of parameters that are to be chosen from standardised values (profile dimensions, motor sizes, gears with different gear ratios etc.) as well as parameters that may vary freely (profile length, controller parameters, actuator attachment points etc.).

The use of automated topology generation is further elevated and the design task further complicated - due to the fact that despite the vast amount of standardised components, the designer of mechatronic systems can not allow oneself to be overly limited by, e.g. standard component configurations. Today (special) components or parts are increasingly customized to meet specific customer demands with respect to functionality and performance.

2 OPTIMISATION BASED DESIGN METHODS

In this section a new paradigm for the design of mechatronic systems is investigated and put forward - **Mechatronic system design** being defined as *the synergistic integration of mechanical engineering, electronics, intelligent control, and systems thinking in the design of smart products and processes*. It is therefore a very interdisciplinary undertaking, where knowledge from different domains has to be integrated in an optimal way. It stands apart from **Mechatronics** understood as an interdisciplinary subject attracting contributions from all related fields without really putting forward the opportunities and challenges arising specifically due to the interdisciplinary interactions, see figure 1.

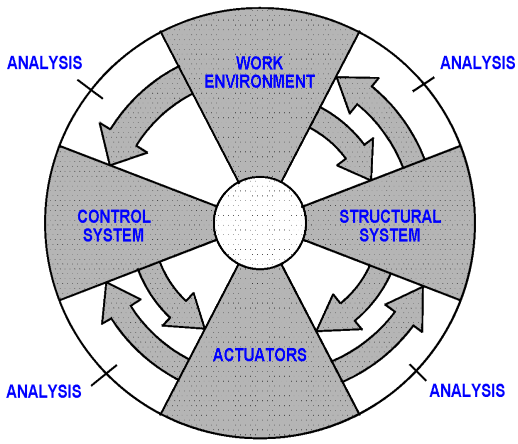

Figure 1: Synergism and integration in mechatronic system design.

The novelty in the idea presented in this paper is to extend the use of algorithm based optimisation to serve as a design tool in mechatronic system design. An algorithm based optimisation here means that the problem is formulated in terms of an objective function, i.e. a mathematical function describing the design goal(s), that should be minimised and where the allowed variations in the design variables are described by a number of constraints, like:

$$\text{minimise} \quad f(\underline{x}) \quad \text{for} \quad \underline{x} \in R^n \tag{1}$$

subject to the constraints:

$$\begin{aligned} \underline{h}\,(\underline{x}) &= \underline{0} \\ \underline{g}\,(\underline{x}) &\leq \underline{0} \end{aligned} \tag{2}$$

The primary goal is to develop methods, i.e. formulate the optimisation problems, that are capable of handling both the control architecture and the mechanical system of complex mechatronic systems. It is in this regard considered essential to the design objective that the developed methods can operate simultaneously at a concept level and a sizing level while being capable of including commercially available components.

The results of the project can be used by manufacturers of multi-technological systems and point out how the integration of disciplines lead to new degrees of freedom in design; it leads to new research fields and at the same time helps to push research in related fields into new directions.

2.1 Background and Research areas

A general discussion on inter-disciplinarity in research, its lack in academia and its tremendous importance for the next century is presented in [1]. Large studies are referred to in which it is concluded that the technology cannot be partitioned according to conventional disciplines.

Today the engineering of mechatronic systems and products typically implies a subsystem-based approach [2]. By subsystem-based approach is here meant a product development strategy by which integrated systems are built from technology homogeneous subsystems (actuators, mechanics, electronics, control and software). The subsystems are developed in a concurrent manner with an important focus on subsystem interfaces. Once the interfaces are designed, each subsystem is designed in a fairly traditional way. A typical design scenario is that an early conceptual design phase results in a coarse partitioning of functionality between mechanics and control software. Based on this, an initial mechanical design is performed. This design provides a basis for modelling of system dynamics that in turn provides input to the control design. This is further developed to real-time software. This means that the focus has been on team building to improve communication and multidisciplinary understanding between engineers of different expertise such that the interfaces can be properly defined. In the subsystem-based approach the performance of the system is a result of a sound integration of existing technology [2]. In the existing engineering literature on mechatronics, the subsystem-based approach is mostly predominant, with limited coverage of the development process etc. [3, 4]. Thus, the literature today does not give an approach for mechatronics engineering.

An interpretation of the above is that state-of-the-art in mechatronics engineering is about mastering a multitude of disciplines, whereas mechatronics as an *engineering science* focuses on interactions among components in different technologies, figure 2.

The strong interaction of technologies (mechanics, control, software, electronics) leads to strong interdependencies that influence, for example, performance and reliability in a way that can only be handled and exploited in a real multidisciplinary environment of a substantial size.

Research activities in systems integration should therefore be directed toward operational systems in order to be really useful from an industrial viewpoint.

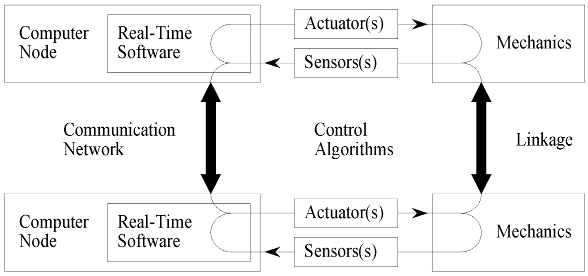

Figure 2: Interactions within an mechatronic system.

To overcome these problems, we need a mathematically well-founded theory that integrates models for the heterogeneous components. Without such a theory, the design will invariably remain at the sub-system level. The research challenge being:

1. In the process of transferring the functionality from mechanics to control, the idea is typically to simplify the mechanical design and/or improve the control performance. This needs new control methods based on better models of the mechanical system. The ideal mechatronic solution to this problem would be that the deficiency of the mechanical system could be cost-effectively compensated for by a suitable control engineering solution. An example is the development of control methods for systems involving multiple nonlinearities (friction, backlash, saturation, etc.) combined with mechanical flexibility.

2. Another research challenge concerns how to best combine different modelling concepts in order to support the development of complex industrial systems characterized by: 1) a combination of event- and time-triggered parts with respect to both requirements and implementation, 2) a combination of discrete-event and discrete-time and continuous-time dynamic systems, and requirements on functionality, timing, reliability, safety, etc.

2.2 Research method- Optimisation

Optimisation methods have been used extensively in a number of fields. Within structural and mechanical system several formulations has been used with great success. In control theory an entire area is devoted to optimal control considered a mature discipline. The handling of discrete design variables is also well developed today utilizing different genetic algorithms. Especially, within the area of fluid power some work has been devoted to the simultaneous design at concept and sizing level, see for example [5, 6, 7 and 8]. In [5] the use of commercially available components are introduced by means of databases.

However, to the knowledge of the principal investigators no methods have been developed with the main purpose of handling the design of mechatronic systems that include all of the above areas simultaneously. The main obstacle is the combination of the inherent difficulties mentioned in the second research challenge and, equally important, the needed ability to handle and evaluate different design concepts. These obstacles are the main reason why optimisation as a tool is not more widespread in industry today.

Since the mid-nineties the authors have devoted a substantial part of their research to design and design methods. Initially, emphasis was on the sizing of mechanical mechanisms based on purely mechanical criteria; see [9, 10, 11] although the concept level also has been addressed [12]. The inclusion of actuation was introduced by sizing of hydraulically actuated manipulator systems [13, 14, 15, 16], and later, optimal control aspects was included in [17, 18, 19, 20] but still at a purely sizing level. The concept level on actuation systems was introduced in [21] and further developed to handle hydraulic-mechanical systems in [22, 23]. Recently, the discrete design variables and the use of commercially available components have been addressed in [24] on electrically actuated servo driven robots, and further developed to include a certain degree of concept level [25] on hydraulically actuated scissor tables. The applied methods have been optimisation utilizing either gradient or non-gradient based search algorithms or genetic algorithms whenever discrete design variables have been present. However, in the recent works [24, 25] some very encouraging new results have been obtained using mapping techniques that allow the inclusion of discrete design variables, commercially available components and design variations at concept level simultaneously and, at the same time, avoiding the time consuming genetic algorithms. These results give confidence that the research challenges of mechatronic system design can be met successfully.

3 CONCLUSION

This paper has placed its emphasis on integrated modelling and design optimisation. R&D activities have become more customer-driven than ever before, and therefore simulation tools for research and development, with strong emphasis on drastically accelerating the product introduction process has become more and more important. This, in turn, calls for a high degree of predictability of the initially developed design, with a reduced dependency on prototypes and an increased dependency on simulation and automated design procedures.

- Only well understood/well described sub systems with a high degree of predictability in behaviour should be used as building blocks.

- An automated procedure that determines not only the dimensions but also the topology should be employed using either a serial or a concurrent technique.

In the authors view PDP is the design approach to be used in system design of the future. Parallel to this, experimental and scientific work will continuously increase the design space, i.e., the amount of sub systems applicable to the PDP design approach.

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